On-Board Satellite Implementation of Wavelet-Based Predictive Coding of Hyperspectral Images

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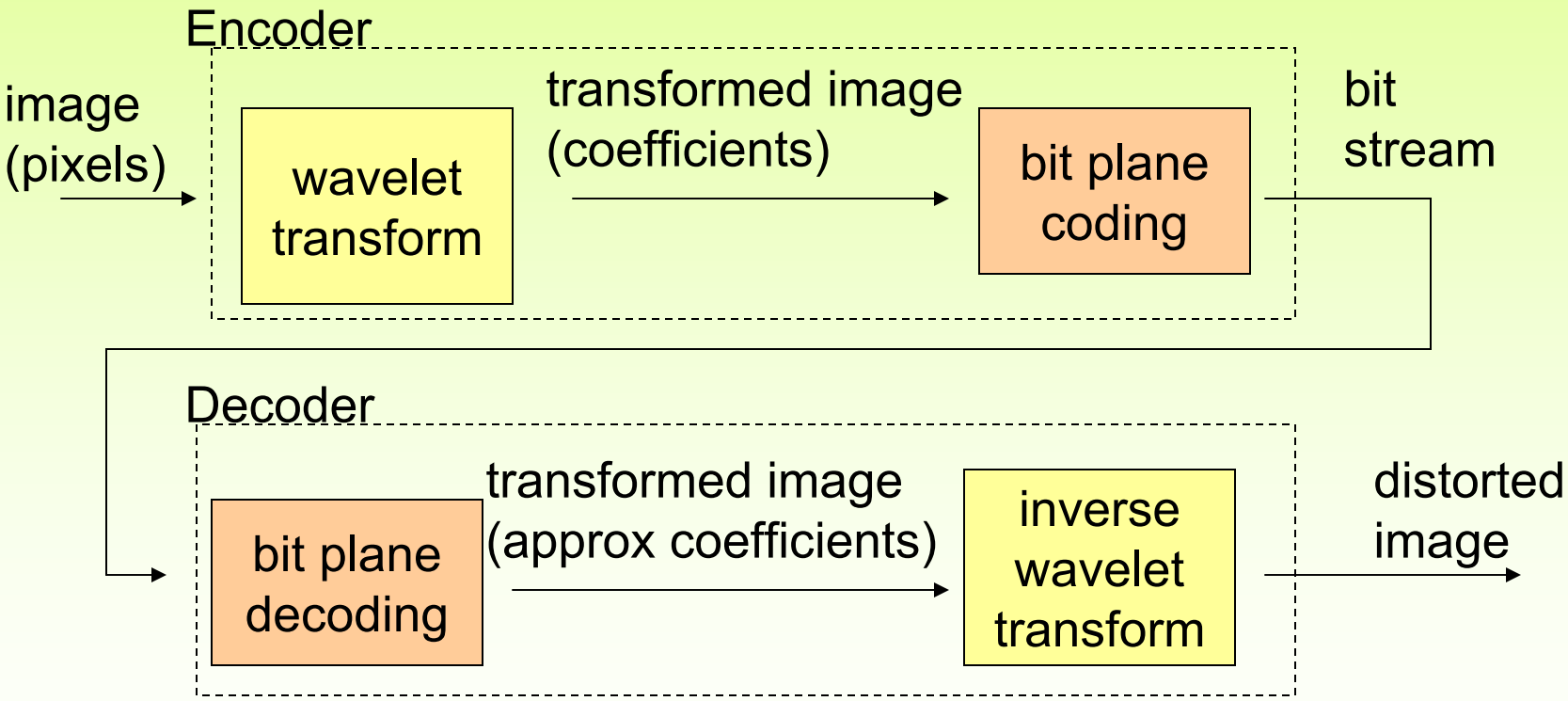
Introduction

- Lossy image compression (SPIHT)
  - wavelet transform
  - bit plane coding
- SPIHT on hyperspectral data
  - linear prediction
- Implementation on-board the satellite
  - FPGAs

SPIHT

- Set Partitioning in Hierarchical Trees (SPIHT)
  - Said and Pearlman'96.
- Wavelet-based, state-of-the-art lossy image coder
- Progressive, bit plane-based coding (embedded bit stream)
- Coding for bit rate or Peak Signal-to-Noise Ratio (PSNR)

SPIHT


Encoder
image
(pixels)
wavelet
transform
transformed image
(coefficients)
bit plane
coding
bit
stream
Decoder
bit plane
decoding
transformed image
(approx coefficients)
inverse
wavelet
transform
distorted
image

Wavelet transform

- Transform the input pixels (16-bit integers) into coefficients (real values)
- Most of the image energy is compacted into a few coefficients.

Wavelet Transformed Image

2 levels of wavelet transform

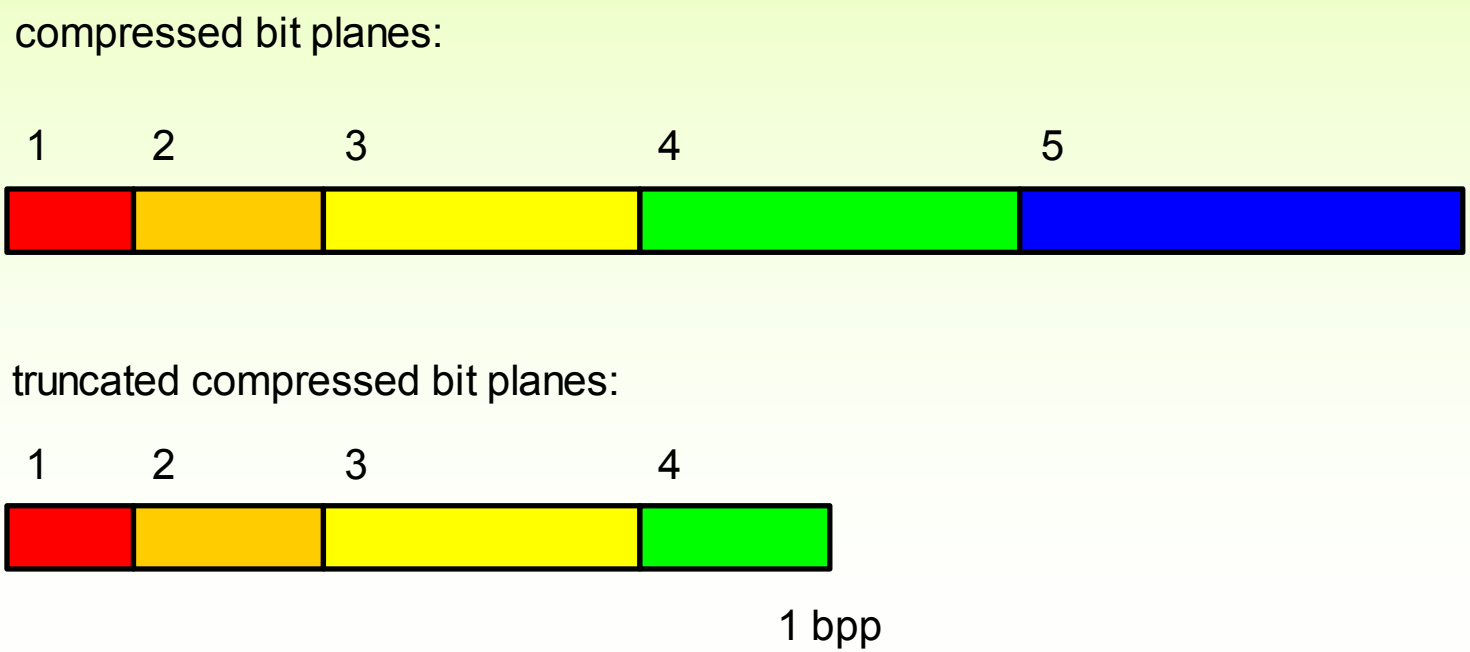
1 low resolution subband

6 detail subbands

(subbands were enhanced to show detail)

Bit plane coding

- Wavelet coefficients are transmitted in bit-plane order
- Only some of the bit planes are transmitted. This is where fidelity is lost when compression is gained.



Bit plane coding

- In most significant bit planes most coefficients are 0
  - they can be coded efficiently
- Bit plane coding and decoding take significantly more time than the wavelet transform

SPIHT on hyperspectral data

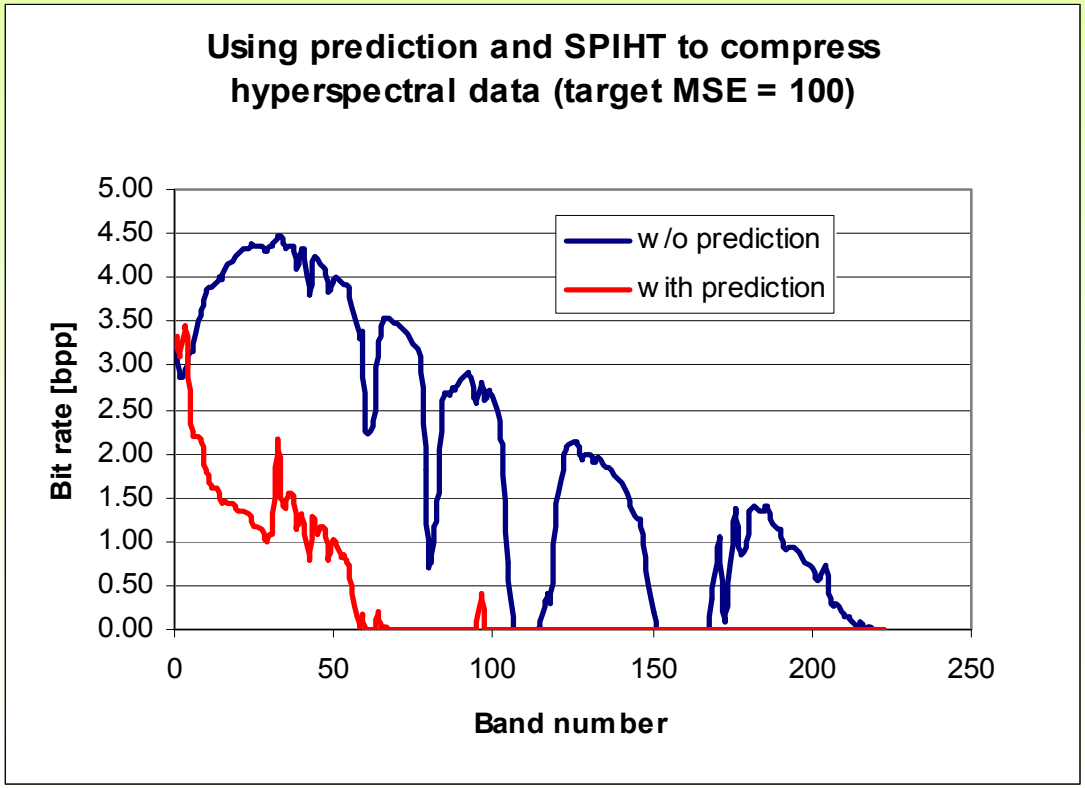
- Use linear prediction to take advantage of correlation between bands:
  - predict the current band B_i from a previous band B_j
  - compute the difference D_i between the original band B_i and the predicted band P_i
  - code the differences to the same Mean-Squared Error (MSE)

$$P_i = a_{ij} B_j + b_{ij}$$

$$D_i = B_i - P_i$$

$$B_i = P_i + D_i$$

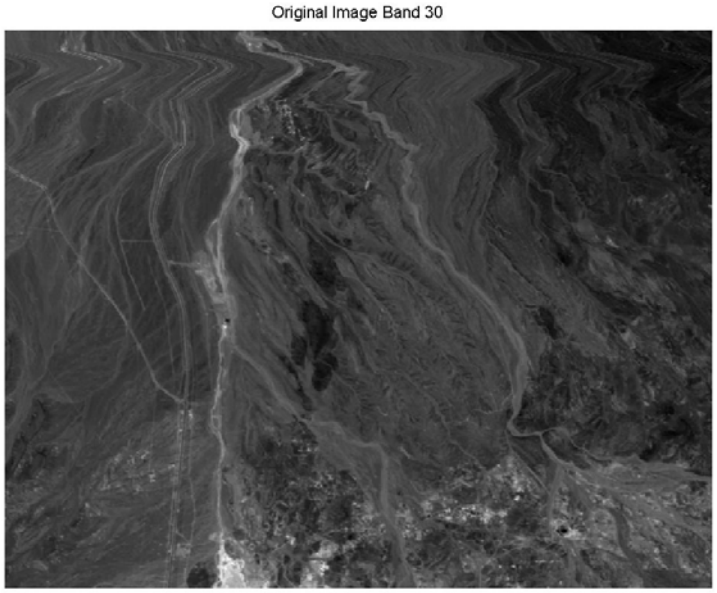
Effect of prediction on compression



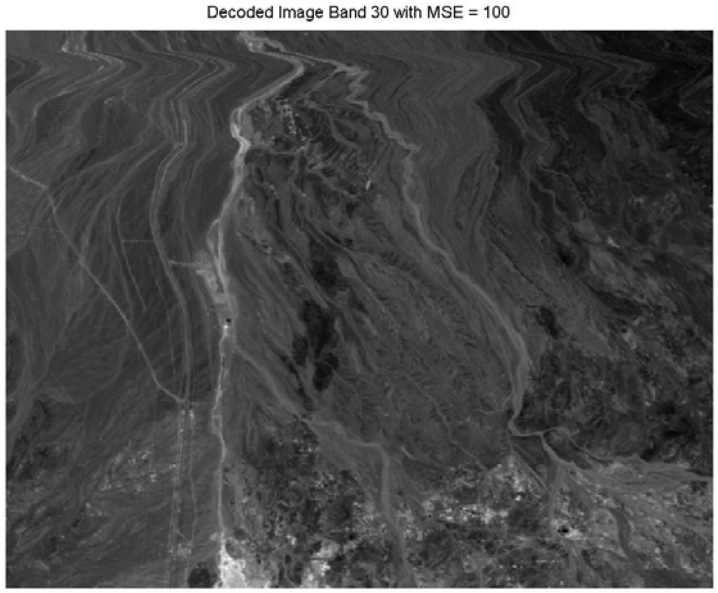
- Average bit rate:
  - without prediction:
    1.99 bpp
    (8 : 1 ratio)
  - With prediction:
    .37 bpp
    (43 : 1 ratio)

Example band

- Band 30 predicted from band 29
  - MSE = 100
  - Original 16 bpp
  - Without prediction 4.37 bpp (3.7 : 1 ratio)
  - With prediction 1.1 bpp (14.6 : 1 ratio)



Original



Decoded

Prediction study

- Cuprite image
  - 224 bands
  - 16-bit signed integers
  - 614 pixels/line x 512 lines
- Reverse prediction order
- Results shown for MSE = 100

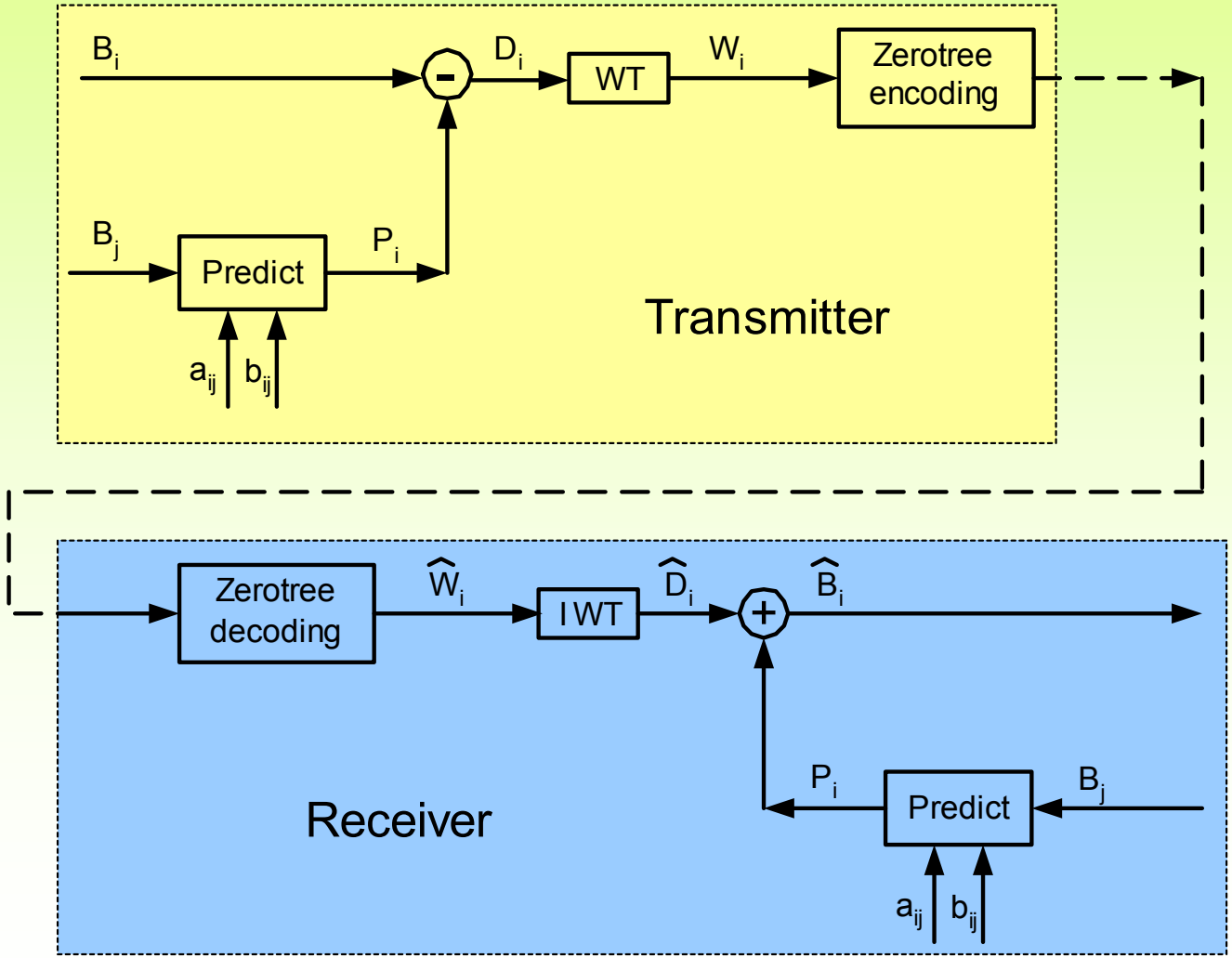
Prediction with SPIHT

- To predict the current band, the previous band is needed.
  - the previous band can be the original or the decompressed band
- Types of prediction:
  - open loop
  - half-open loop
  - closed loop
  - bit plane-synchronized closed loop

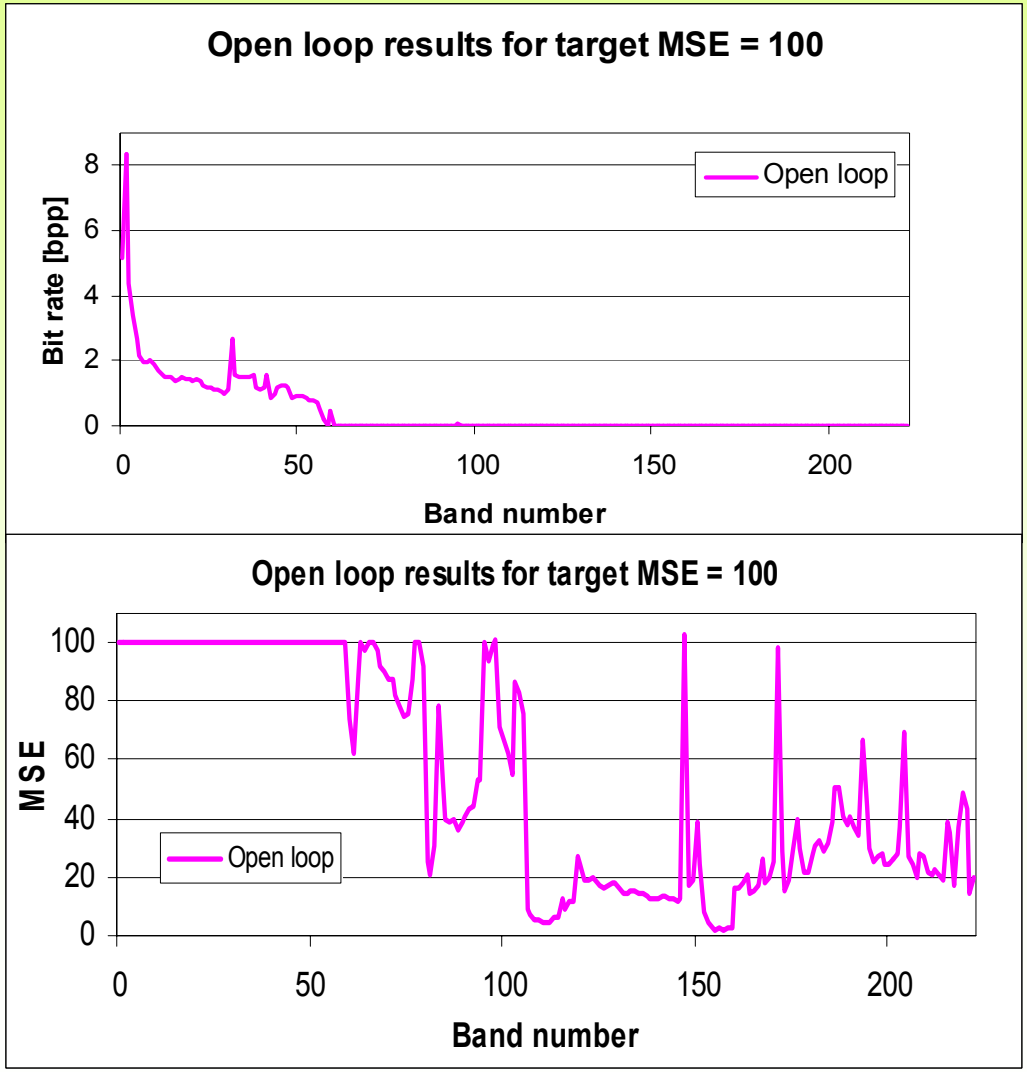
Open loop prediction

- Both transmitter and receiver use original band for prediction
- Not possible because the receiver cannot have the original band!

Open loop prediction



Open loop prediction

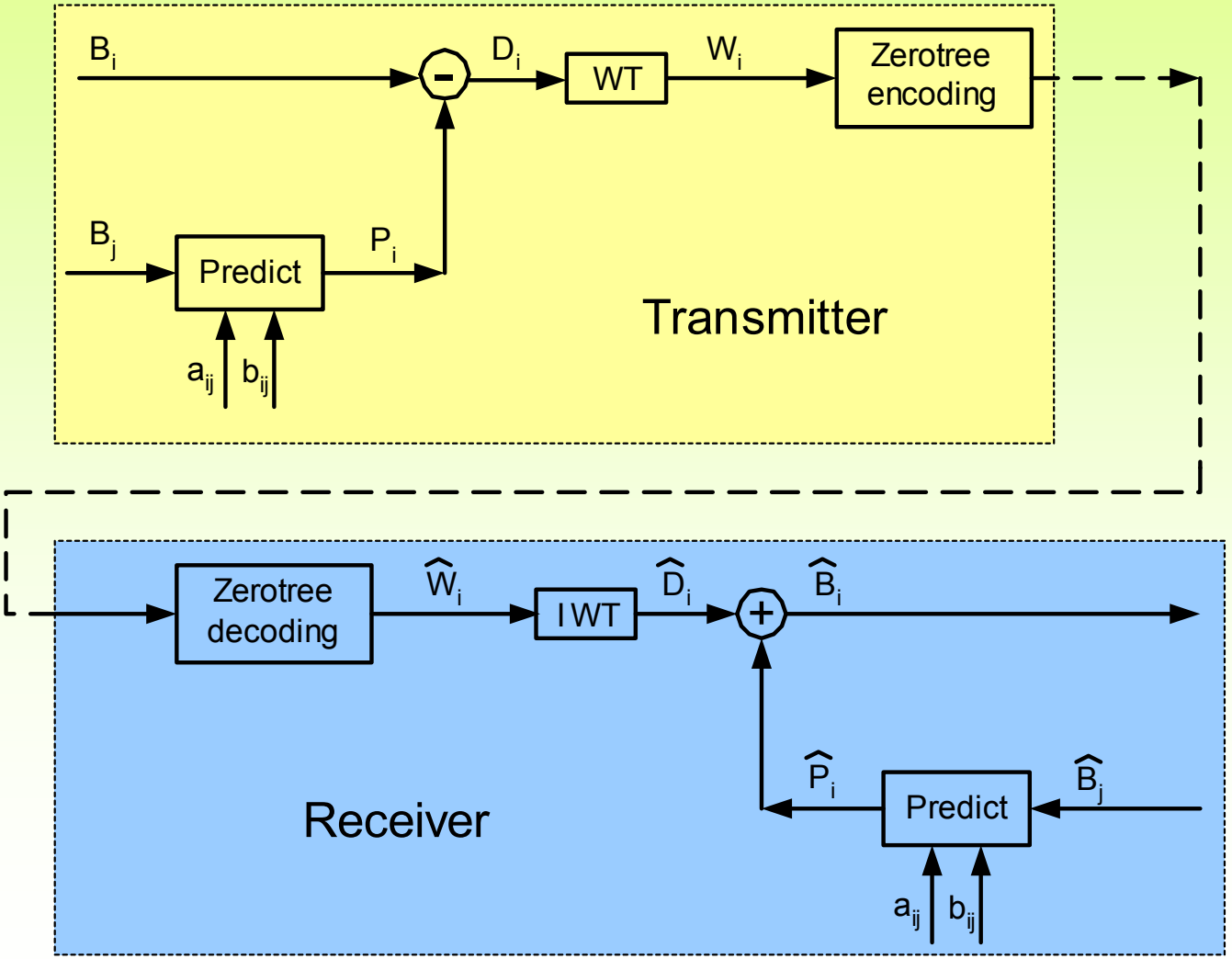


- Average bit rate:
  0.42 bpp
  (38 : 1 ratio)
- Average MSE:
  53.73

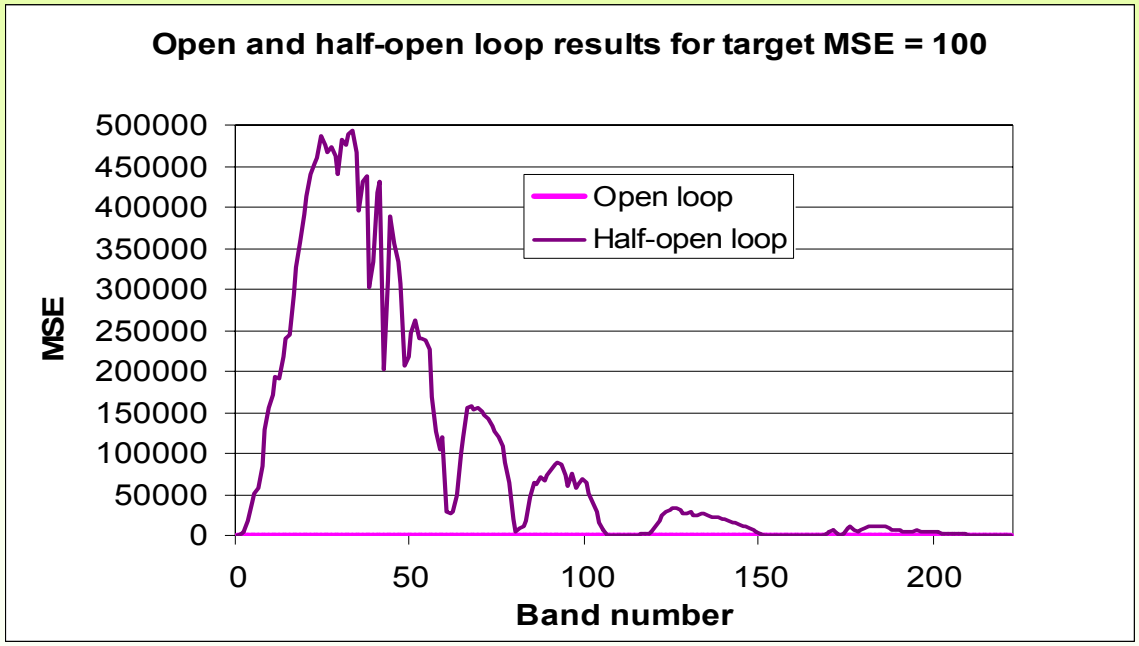
Half-open loop prediction

- Transmitter uses original previous band for prediction
- Receiver uses previous decompressed band for prediction
- Leads to lack of synchronization between the transmitter and the receiver and large errors.

Half-open loop prediction



Half-open loop prediction



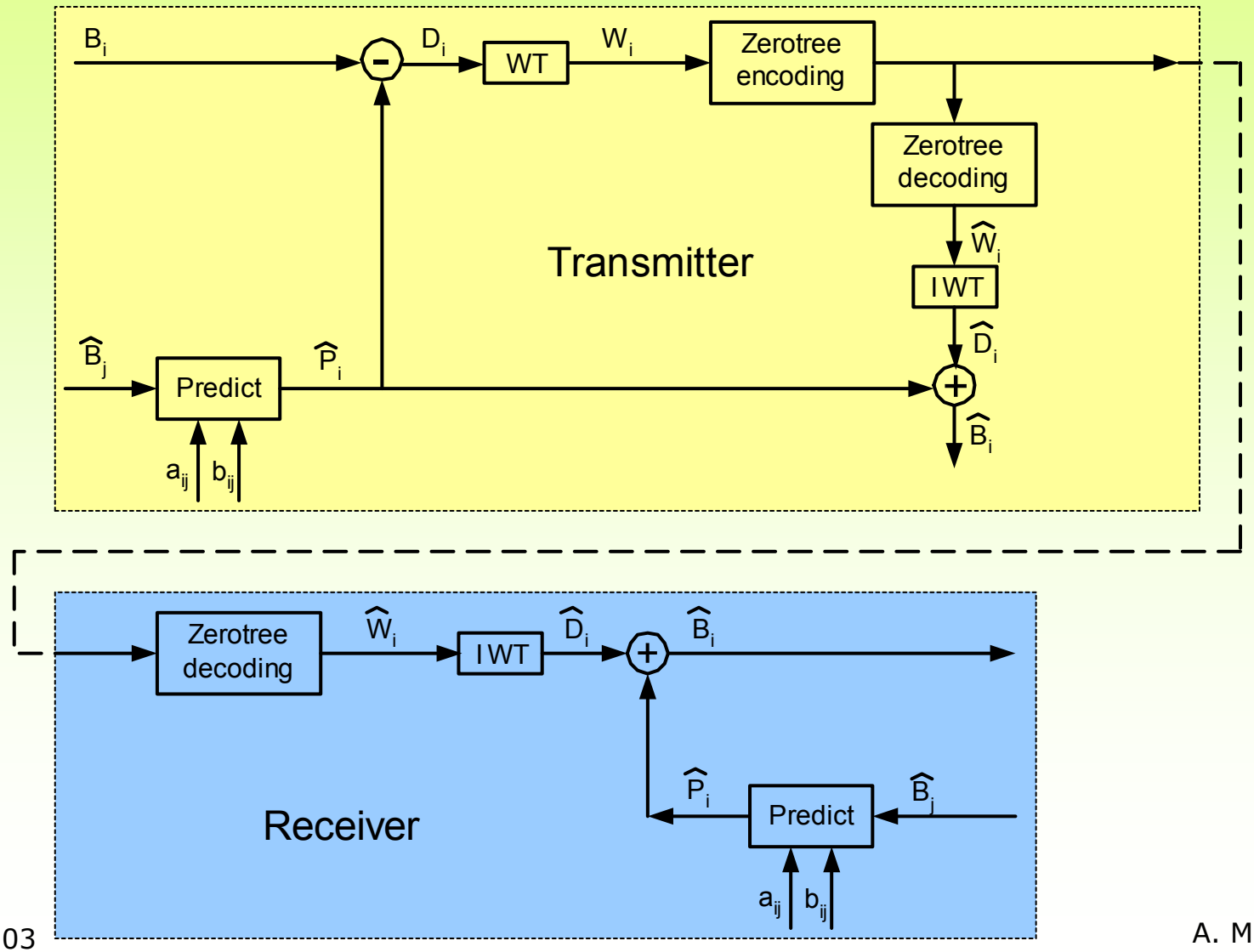
- Average bit rate (same as open loop):
  0.42 bpp
  (38 : 1 ratio)

- Average MSE:
  - open loop:
    - 53.73
  - half-open loop:
    - 96502.40

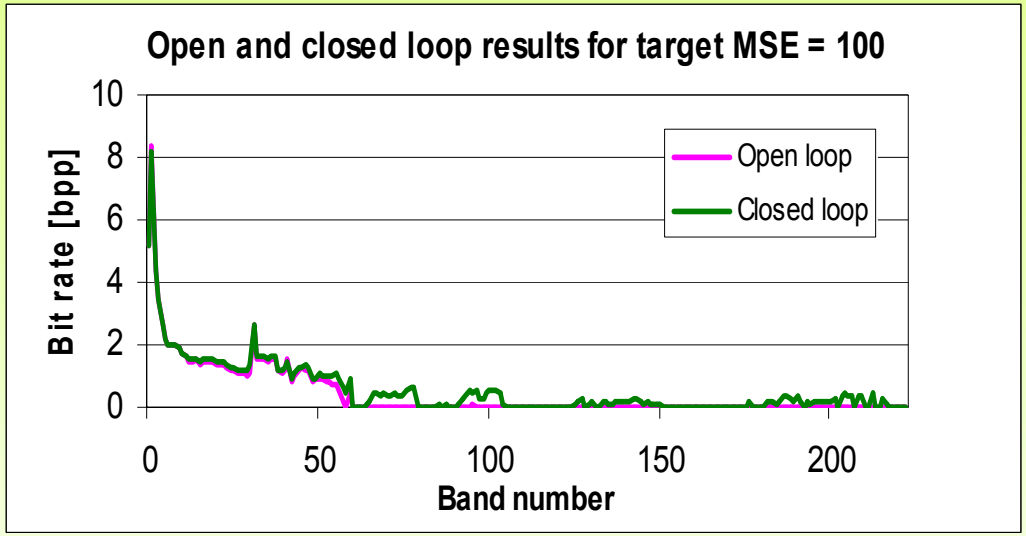
Closed loop prediction

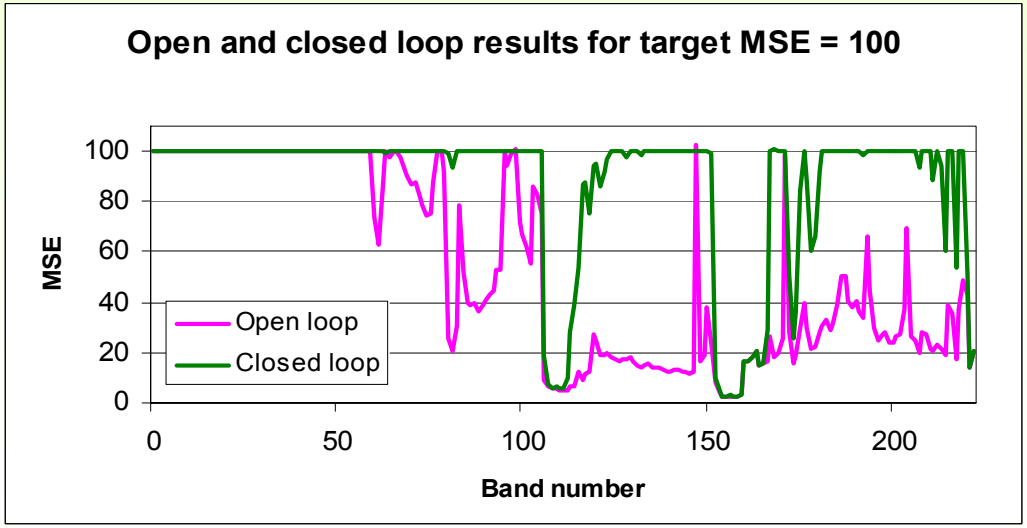
- Both transmitter and receiver use decompressed previous band for prediction.
- Most accurate method.
- Too complex for on-board application: requires the transmitter to implement the decoder, which is computationally complex.

Closed loop prediction



Closed loop prediction



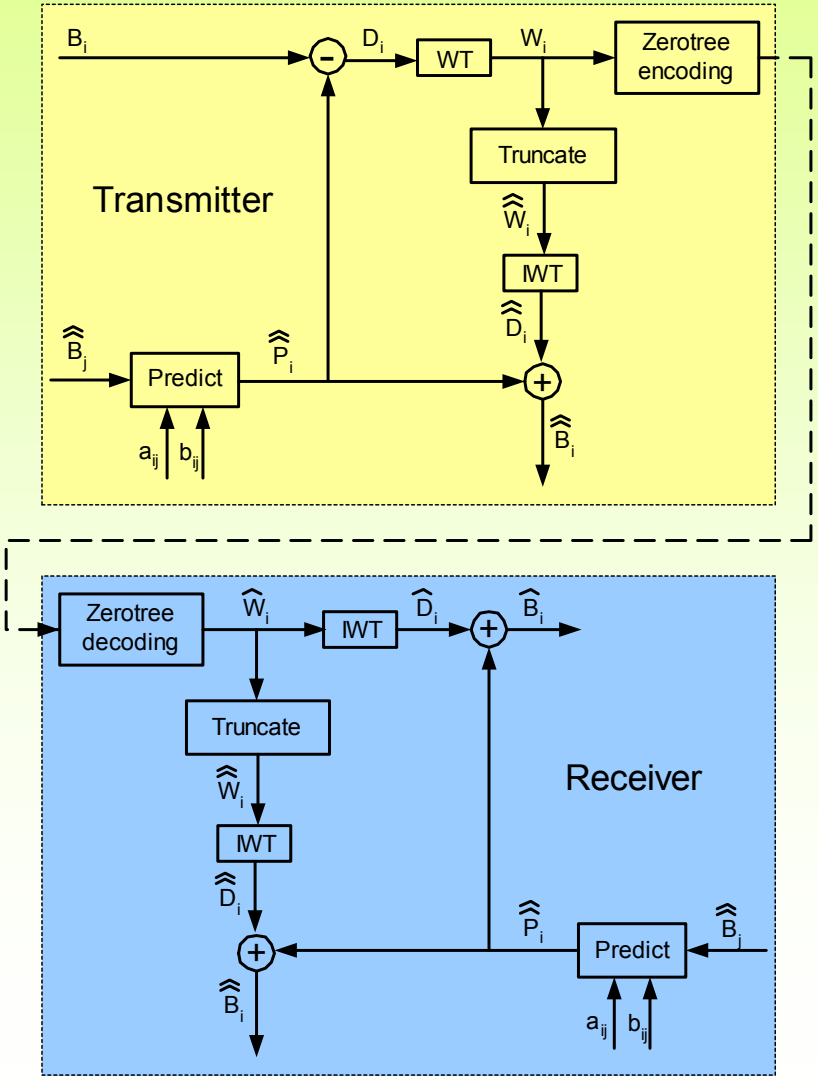


- Average bit rate:
  - open loop:
    0.42 bpp
    (38 : 1 ratio)
  - closed loop:
    0.55 bpp
    (29 : 1 ratio)
- Average MSE:
  - open loop:
    53.73
  - closed loop:
    87.09

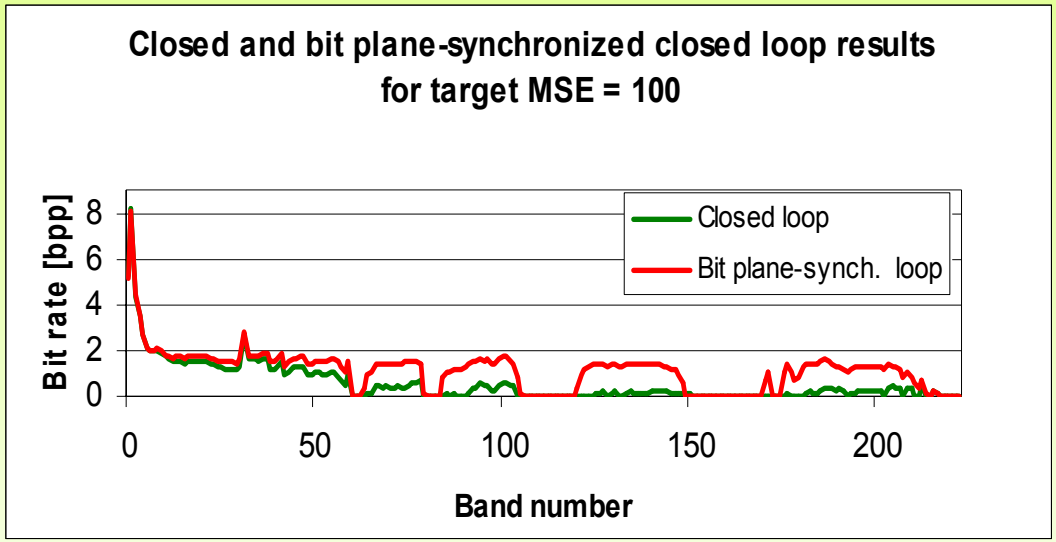
Bit plane-synchronized closed loop

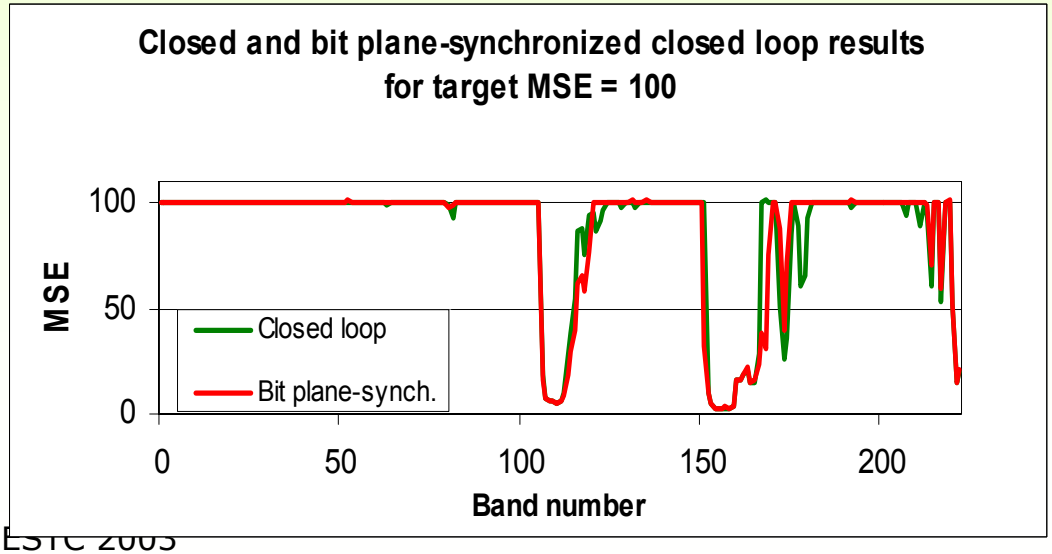
- Both transmitter and receiver use the same number of bit planes of the wavelet coded difference image of the previous band for prediction.
- The on-board transmitter is simpler:
  - It has to perform an inverse wavelet transform, but not a full decompression (zerotree decoding) as part of the prediction process.

Bit plane-synchronized closed loop



Bit plane-synchronized closed loop





- Average bit rate:
  - closed loop:
    0.55 bpp
    (29 : 1 ratio)
  - bit plane-synchronized closed loop:
    1.12 bpp
    (14 : 1 ratio)
- Average MSE:
  - closed loop:
    87.09
  - bit plane-synchronized closed loop:
    87.15

Improvements

- Compute new prediction coefficients
- Better rate control:
  - decision to round up or down
  - thresholds (typical values: 0.1 – 1.0)

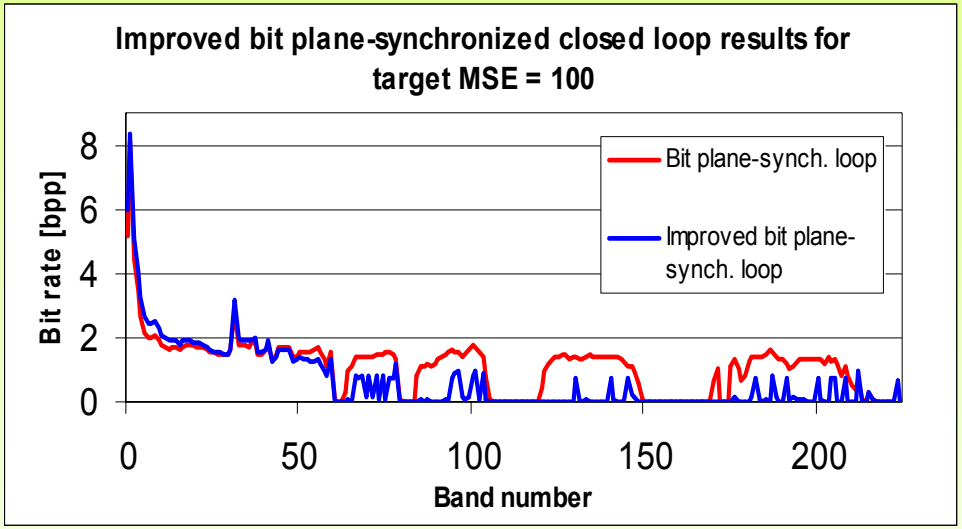
$$\text{if } \left| R(W_i) - R\left(\hat{\hat{W}}_i^{k}\right) \right| < T \left| R(W_i) - R\left(\hat{\hat{W}}_i^{k+1}\right) \right|$$

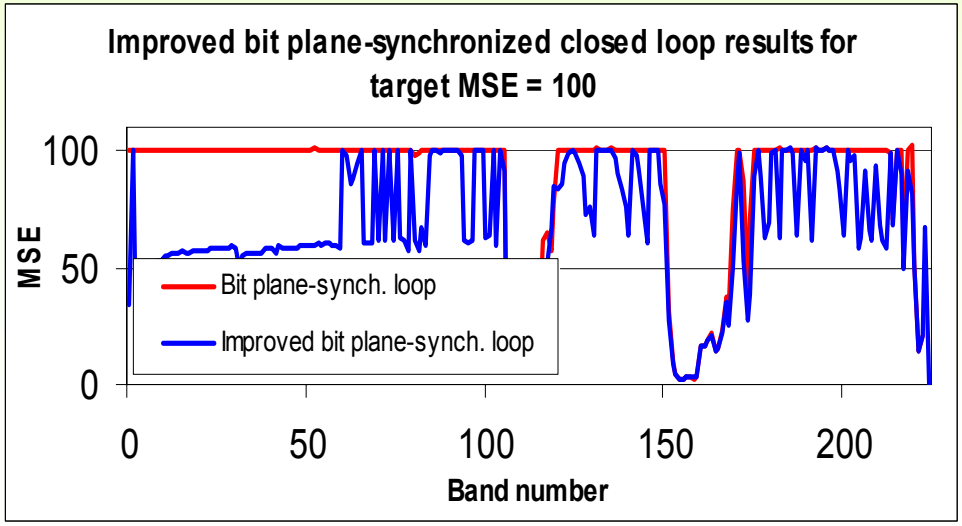
select k bit planes for prediction

else

select $k+1$ bit planes for prediction and transmission

Improvements





- Average bit rate:
  - bit plane-synchronized closed loop:
    1.12 bpp
    (14 : 1 ratio)
  - improved bit plane-synchronized closed loop:
    0.65 bpp
    (24 : 1 ratio)

- Average MSE:
  - bit plane-synchronized closed loop: 87.15
  - improved bit-plane synchronized closed loop: 66.66

Conclusions

- Using prediction to code hyperspectral data significantly improves the compression ratio.
- Benefits of the proposed bit plane-synchronized closed loop:
  - Lower computational complexity compared to the closed loop approach
  - Easier to implement on-board the satellite
  - Very good compression ratio with low MSE

Future work

- Universality
  - Study how the above results translate to other hyperspectral data
- Continue improving the bit plane-synchronized closed loop
  - Better rate control using look ahead
    - What is the influence of the current band's rate on the rate of the future band predicted by it.
- Different metric
  - Maximum error instead of MSE